Compensation by nonoperated joints in the lower limbs during walking after endoprosthetic knee replacement following bone tumor resection

腫瘍用人工膝関節置換術後患者の歩行時の手術膝以外の下肢関節による代償戦略

沖田　祐介

NOTICE: This is the author's version of a work accepted for publication in *Clinical Biomechanics*. Changes resulting from the publishing process, including peer review, editing, corrections, structural formatting and other quality control mechanisms, may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. The definitive version has been published in *Clinical Biomechanics*, volume 28, issue 8, November 9, 2013, DOI 10.1016/j.clinbiomech.2013.08.005.

Compensation by nonoperated joints in the lower limbs during walking after endoprosthetic knee replacement following bone tumor resection

Yusuke Okita[a,b*], Noriatsu Tatematsu[c], Koutatsu Nagai[d], Tomitaka Nakayama[e], Takeharu Nakamata[f], Takeshi Okamoto[g], Junya Toguchida[h], Shuichi Matsuda[g], Noriaki Ichihashi[a], Tadao Tsuboyama[a]

[a] Department of Physical Therapy, Human Health Sciences, Graduate School of Medicine, Kyoto University, Kyoto, Japan

[b] Research fellow, Japan Society for the Promotion of Science, Tokyo, Japan

[c] Department of Rehabilitation, Kobe Minimally Invasive Cancer Center, Kobe, Japan

[d] Faculty of Health Science, Department of Physical Therapy, Kyoto Tachibana University, Kyoto, Japan

[e] Department of Orthopaedic Surgery, Toyooka Hospital, Hyogo, Japan

[f] Department of Orthopaedic Surgery, Rakuwakai Otowa Hospital, Kyoto, Japan

[g] Department of Orthopaedic Surgery, Kyoto University, Kyoto, Japan

[h] Department of Tissue Regeneration, Institute for Frontier Medical Sciences, Kyoto University, Kyoto, Japan

Corresponding author:

Yusuke Okita

Department of Physical Therapy, Human Health Sciences, Graduate School of Medicine, Kyoto University, 53, Kawaharacho, Shogoin, Sakyo-ku, Kyoto-shi, Kyoto 606-8507, Japan

Word count for the abstract: 245

Word count for the main text (excluding reference): 2829

Number of Tables: 3

Number of Figures: 3

Abstract

Background: Endoprosthetic knee replacement is often used to preserve joint function in patients with bone tumors of the distal femur or proximal tibia. Recently, because of improved oncologic outcome, surgeons are focusing more on the functional outcome of patients with musculoskeletal tumors. We hypothesized that patients who have undergone endoprosthetic knee replacement are forced to compensate for deficiency in their operated joint during walking. In this study, we investigated differences in gait kinematics, kinetics, and energetics between patients with endoprosthetic knee replacement and healthy subjects.

Methods: We performed gait analysis for 8 patients who underwent endoprosthetic knee replacement after bone tumor resection and 8 matched healthy subjects. Gait kinematics, kinetics, and energetics of patients' ipsilateral and contralateral limbs were compared with those of healthy subjects by using Dunnett's test.

Findings: Compared with healthy subjects, patients showed increased negative joint power around the ipsilateral ankle, greater second peak in the contralateral vertical ground reaction forces, and abnormal hip movement on both sides after initial contact.

Interpretation: Patients tended to compensate for dysfunction of the reconstructed knee by muscles around the ipsilateral ankle and contralateral hip, with increased load on the contralateral limb during walking. These differences could lead to secondary impairments. Further analysis, including

musculoskeletal simulation and assessment of long-term functional outcome with regard to secondary musculoskeletal impairment, is needed to verify the significance of the change in gait and to determine the need for special care for secondary musculoskeletal dysfunction in these patients.

1. Introduction

Endoprosthetic knee replacement is often used to preserve joint function in patients with bone tumors of the distal femur or proximal tibia. Recently, surgeons are focusing more on the functional outcome of patients with musculoskeletal tumor because of improved oncologic outcome (Whelan et al., 2011) with the help of advanced diagnostic imaging, chemotherapeutic agents, and surgical techniques. For orthopedic surgeons, gait function is one of the most important components of functional outcome in patients treated for a tumor in the lower extremity. Previous studies have reported slower walking speed (Carty et al., 2009; De Visser et al., 2000; Otis et al., 1985), longer step length of the nonoperated limb (Rompen et al., 2002), and decreased foot pressure (Tsuboyama et al., 1994), all of which can be attributed to insufficient muscle strength around the reconstructed knee.

These patients have to compensate for deficiency of the reconstructed joint by using muscles around adjacent or contralateral joints during walking. This compensation can be quantitatively evaluated by analyzing gait kinematics (e.g., joint angular movement), kinetics (e.g., ground reaction forces and internal joint moment), and energetics (e.g., joint power). However, because there is little knowledge on how joint kinematics, kinetics, and energetics change after endoprosthetic knee replacement following bone tumor resection, it is difficult to consider the potential overload on musculoskeletal tissue around the lower limb joints other than the reconstructed knee. Previous studies have suggested the possibility of increased load on nonoperated joints during locomotion after bone or joint reconstruction (Beaulieu et al., 2010; Foucher and Wimmer, 2012; Taddei et al., 2011). The aim of this study was to verify compensation by nonoperated joints during walking in patients who underwent endoprosthetic knee replacement following bone tumor resection by evaluating differences in lower limb gait biomechanics between patients and healthy subjects.

2. Methods

2.1. Study design

This was a single-center, cross-sectional study based on measurements obtained from a group of patients and a group of healthy control subjects. Patients aged >15 years who underwent endoprosthetic knee replacement after bone tumor resection, were without neurologic musculoskeletal pathology that affected gait function, and were routinely followed-up at Kyoto University Hospital were included. Exclusion criteria were concurrent metastasis, local recurrence, unstable implant, period of less than 1 year since last surgery, daily use of walking aid or orthopedic shoes, and more than 3 cm of discrepancy in limb length. All eligible patients were asked to participate in the study at the outpatient clinic, and, if they agreed to be part of the study, measurements were obtained at a motion analysis laboratory on another day. After collecting the patients' data, we recruited matched healthy subjects whose data were compared with the patients' data. All procedures were approved by the Ethical Review Board of Kyoto University Graduate School of Medicine, and written informed consent was obtained from all subjects.

2.2. Data collection and processing

We performed gait analysis using a 7-camera 3-dimensional motion analysis system (Vicon MX; Vicon, Oxford, United Kingdom) with 2 force plates (9286A; Kistler Japan, Tokyo, Japan). All participants (patients and healthy subjects) walked along a 6-m walkway at a self-selected speed with 35 retroreflective markers on their body landmarks, according to the Plug-in Gait protocol (Vicon). All healthy subjects also walked at a slightly slower speed because patients who have undergone endoprosthetic knee replacement may walk more slowly than healthy subjects (Carty et al., 2009; De Visser et al., 2000; Otis et al., 1985). The walking speed of each healthy subject (either self-selected or slower) that was closer to the mean walking speed of the patients was used in analysis. At least 5 successful trials were collected for each walking speed (self-selected for both groups and slower for healthy subjects) to assure repeatability of the results. Data were collected at a sampling rate of 100 Hz for marker trajectories and 1,000 Hz for force plates.

Marker trajectories were filtered using a Woltring filter (Woltring, 1986), with a mean-squared error value of 10. Joint kinematics and kinetics were generated using inverse dynamics analysis within Nexus version 1.7.1 software (Vicon). Joint moments were filtered using a 0-lag fourth-order Butterworth filter. Joint powers were calculated from the dot product of the joint angular velocities and joint moments on the sagittal plane. Joint moments and powers were normalized to body weight and height. Joint power is the energy generated (positive value) or absorbed (negative value) around a joint per unit of time. All data were processed using Nexus software and MATLAB 2012a (MathWorks, Natick, MA).

2.3. Statistical methods

Walking speeds were reported as the mean and SD for patients and healthy subjects. Ground reaction forces, joint angles, joint moments, and joint powers were averaged for each of 3 groups (ipsilateral and contralateral sides of the patients, and the right side of healthy subjects). We compared the joint kinematic, kinetic, and energetic parameters described in Table 1 between the 3 groups using Dunnett's multiple comparison test, performed on R version 2.41.0 (R Development Core Team, http://www.R-profect.org) with an R library multcomp (Hothorn et al., 2008), setting the right side of healthy subjects as the control group. Significance was set at $P < .05$. The patients' ipsilateral limb was not compared with the contralateral limb because the presence of a compensatory mechanism cannot be determined by comparing data obtained from the same patient. All graphics were generated by R.

3. Results

Of 17 eligible patients, 9 were excluded: because of implant instability in 3, daily use of crutches or a cane in 2, metastasis in 1, and refusal to participate in 3. Finally, 8 patients (mean [SD, range] age, 30 [12, 19–59] years; height, 1.67 [0.7, 1.58–1.78] m; weight, 59.9 [20.2, 45.0–108.5] kg) who underwent endoprosthetic knee replacement following bone tumor resection participated in this study at a mean (SD) of 91 (41) months after primary endoprosthetic replacement. Demographic data of the patients are shown in Table 2. Of the 8 patients, 6 had osteosarcoma, 1 had giant cell tumor, and 1 had chondrosarcoma. Five patients had a tumor in the distal femur and 3 in the proximal tibia. Four patients had undergone revision surgery; only a femoral component had been replaced in 1, only a tibial component had been replaced in 1, and all components had been replaced in 2. All patients were continuously disease free and could walk without an assistive device. Three types of endoprosthesis were used for reconstruction: Kyocera Limb Salvage System (KYOCERA Medical Corp., Osaka, Japan) in 3 patients, Howmedica Modular Resection System (Stryker Orthopaedics, Mahwah, NJ) in 3, and Japan Medical Materials K-MAX KNEE System K-5 (KYOCERA Medical Corp.) in 2 (Fig. 1). Eight matched healthy subjects (mean [SD, range] age, 30 [10, 23–53] years; height, 1.70 [0.06, 1.62–1.78] m; weight, 62.2 [10.9, 48.6–85.0] kg) were enrolled. Mean (SD) walking speed was 1.21 (0.15) m/s for patients and 1.20 (0.08) m/s for healthy subjects.

3.1. Ground reaction forces

Ground reaction forces of patients and healthy subjects are shown in Figure 2. The first (GR3) and second (GR4) peaks of vertical ground reaction forces were smaller on the ipsilateral side in the patients than in the healthy subjects, whereas the second peaks of vertical ground reaction forces were greater on the contralateral side in the patients than in the healthy subjects (Fig. 2, Table 3).

3.2. Joint angles, moments, and powers

Compared with healthy subjects, patients showed a tendency to flex the contralateral hip after initial contact, (Table 3, H5), whereas the ipsilateral hip of the patients simply extended after initial contact (Fig. 3, Table 3, H1-2). The ipsilateral knee of the patients generally remained extended during early stance (Fig. 3, Table 3, K1-3). Of the 8 patients, 5 (3 with femoral replacement) kept their operated knee extended during early stance, whereas 2 (1 with femoral replacement) exhibited a normal knee movement pattern. One patient with femoral replacement flexed the ipsilateral knee after initial contact but extended it during late stance, similar to a normal knee. The maximal plantarflexion angle during early stance was greater on the ipsilateral side of the patients than in the healthy subjects, and the maximal dorsiflexion angle was smaller on the ipsilateral side of the patients than in the healthy subjects (Fig. 3, Table 3, A2-3). The maximal knee extension moment during early stance was smaller on the ipsilateral side of the patients than in the healthy subjects (Fig. 3, Table 3, KM). The maximal plantarflexion moment was smaller on the ipsilateral side of the patients than in the healthy subjects (Fig. 3, AM2). The patients' ipsilateral knee exerted little joint power during early stance (Fig. 3, Table 3, KP1-2). During stance, the mean negative ankle joint power of the patients' ipsilateral side was greater than that of the healthy subjects (Fig. 3, Table 3, AP2).

4. Discussion

We hypothesized that patients who have undergone endoprosthetic knee replacement are forced to compensate for deficiency in their operated joint during walking. In this study, we verified differences in gait kinematics, kinetics, and energetics between patients and healthy subjects matched by age, sex, size (height and weight), and walking speed. Some studies have investigated joint angles, joint moments, and joint power during gait (Benedetti et al., 2000; Carty et al., 2009). However, these studies only discussed the reduction in joint motion or kinetic value and not the increased load on residual intact muscles or joints. We focused on the increases in joint angular movement, moment, and power from the viewpoint of compensation. Defining parameters of interest allowed us to identify the approximate time point at which each maximum (or minimum) value was obtained; this helped us to estimate the potential problems experienced by the patients during walking.

The walking speed of patients after endoprosthetic knee replacement differs between studies (De Visser et al., 2000; Colangeli et al., 2007; Carty et al., 2009), possibly because of variable experimental settings (level or treadmill walking) and/or differences in patient age or tumor treatment. The mean walking speed of patients in the present study is similar to that in a recent study (Carty et al., 2009).

4.1. Ipsilateral knee kinematics

We observed 3 major patterns in the patients' ipsilateral knee kinematics, as previously reported (Carty et al., 2009; Rompen et al., 2002): (1) no ipsilateral knee flexion during early stance (extended-knee gait, 5 patients), (2) no ipsilateral knee extension during late stance (flexed-knee gait, 1 patient), and (3) 2 distinct peaks of knee flexion, the so-called double-knee action, during a stride (normal gait, 2 patients). The causes of the first 2 gait patterns are not clear, although weakness in ipsilateral knee extensors (Rompen et al., 2002), need for knee stabilization during loading response, and compensation for a painful knee (Carty et al., 2009) may be contributing factors~~, as previous studies have discussed~~. Removal of the vastus medialis with relative preservation of the vastus lateralis and vastus intermedius (Benedetti et al., 2000) or guarding the operated knee (Tsuboyama et al., 1994) might be associated with extended-knee gait (also referred to as stiff-legged pattern).

Extended- and flexed-knee gait similarly exhibit smaller sagittal knee excursion, which might lead to increased ipsilateral ankle excursion and ankle joint power during stance. The differences described above were more clearly exhibited by patients with extended- or flexed-knee gait than those with a normal gait pattern.

4.2. Compensation by ipsilateral limb

The results of this study suggest the presence of compensation around the ipsilateral ankle. Increased negative joint power around the ipsilateral ankle implies a greater load on ankle dorsiflexors during loading response and ankle plantarflexors during midstance. Activation of the gastrocnemius occurs for a greater time in patients who have undergone endoprosthetic knee replacement than in healthy people (Carty et al., 2010); this also suggests that patients put a greater load on ipsilateral ankle muscles. Decreased ipsilateral knee flexion during early stance, regardless of gait pattern, may alter ankle energetics because greater angular acceleration and deceleration are required if the knee flexes little after initial contact. This reduction in knee flexion may be associated with increased ipsilateral plantarflexion after initial contact. Patients tended to extend the ipsilateral hip continuously from terminal swing to loading response, regardless of their ipsilateral knee kinematics. We do not believe that this continuous hip extension increases hip joint load. Reduced ipsilateral ground reaction forces may enable patients to extend the ipsilateral hip after initial contact. Weakness in ipsilateral hip extensors in patients who underwent endoprosthetic knee replacement, which has been reported previously (Beebe et al., 2009), may be associated with weaker ipsilateral body support during early stance; however, we did not measure hip muscle strength in the patients. In these patients, we did not observe increased hip extension, which has been reported previously (Rompen et al., 2002), possibly because of the small sample size.

4.3. Compensation by the contralateral limb

A greater second peak in the contralateral vertical ground reaction forces suggests that patients' contralateral limbs are generally exposed to greater load at push-off. We also found that compared with healthy subjects, patients tended to flex the contralateral hip after initial contact. This contralateral hip flexion may be due to the slight discrepancy in limb length (0.75 cm shorter than the contralateral side, on average) or compensation for reduced body support by the ipsilateral limb during late stance, which corresponds to contralateral loading response. Although kinetic and energetic analyses did not reveal the effect of this increased contralateral flexion, this kinematic change may affect the contralateral hip by abnormal loading. One patient occasionally experienced contralateral hip pain after a long walk; this pain may indicate the effect of increased flexion on the contralateral hip.

4.4. Limitations

Our study has several limitations, most due to the characteristics of the subjects. First, we could conveniently recruit only 8 patients and could not guarantee the statistical power of each comparison; this restricted our investigation to only the differences we could detect. Second, the heterogeneous characteristics of the patients, including age, weight, implant design, bone resection length, and resected muscles, made the target population less specific. This heterogeneity may have increased variability in gait parameters and weakened the statistical power. Four of the 8 patients underwent revision surgery, which could compromise the functional outcome. However, we could not exclude these patients, because it would have significantly reduced the statistical power, and comparison using a statistical test would have been impractical. Patients with revision surgery appeared to have gait function comparable to that of patients without revision surgery, possibly because of inclusion criteria, such as the ability to walk without an assistive device. Further studies with strict inclusion criteria that specify the type of prosthesis and size and location of the tumor are required for further understanding gait pathology. Third, there may be a selection bias; patients who participated in this study achieved good functional outcome (e.g., they could walk without an assistive device). Therefore, the results of this study should be regarded as a reference of the patients who achieved good functional outcome. Comparing patients after endoprosthetic replacement with those who underwent simple knee replacement for other orthopedic diseases (e.g., osteoarthritis) would also help clarify the gait characteristics of both patient populations. Fourth, the inverse dynamics analysis used in this study did not allow consideration of the detailed joint load with muscle forces. Detection of change in joint load using electromyography may be difficult because of the changes in properties of patients' lower limb muscles, which hamper intersubject comparison of electromyographic findings. Musculoskeletal modeling may be useful to verify the joint load and muscle forces in these patients. Nevertheless, the information obtained from the present study can be used to explain the gait pattern in patients who undergo endoprosthetic knee replacement and to predict the potential problems during walking for these patients.

5. Conclusions

We observed that patients tended to compensate for dysfunction of the reconstructed knee by muscles around the ipsilateral ankle and contralateral hip, with increased load on the contralateral limb during walking. These changes may cause secondary impairments. Further analysis, including musculoskeletal simulation and assessment of long-term functional outcome, is required to verify the significance of the change in gait and to determine the requirement of special care for secondary musculoskeletal dysfunction in these patients. Quantification of the musculoskeletal load after surgery is important because some patients who undergo joint reconstruction after tumor resection live with the implant for more than 20 years.

Acknowledgement

This work is partially supported by Grant-in-Aid for Japan Society for the Promotion of Science Fellows. We thank KYOCERA Medical Corp. and Stryker Japan Corp. for kindly providing information and samples of their endoprosthetic implants.

References

Beaulieu, M.L., Lamontagne, M., Beaule, P.E., 2010. Lower limb biomechanics during gait do not return to normal following total hip arthroplasty. Gait Posture 32, 269-273.

Beebe, K., Song, K.J., Ross, E., Tuy, B., Patterson, F., Benevenia, J., 2009. Functional outcomes after limb-salvage surgery and endoprosthetic reconstruction with an expandable prosthesis: a report of 4 cases. Arch. Phys. Med. Rehabil. 90, 1039-1047.

Benedetti, M.G., Catani, F., Donati, D., Simoncini, L., Giannini, S., 2000. Muscle performance about the knee joint in patients who had distal femoral replacement after resection of a bone tumor. An objective study with use of gait analysis. J. Bone Joint Surg. Am. 82-A, 1619-1625.

Carty, C.P., Bennett, M.B., Dickinson, I.C., Steadman, P., 2009. Assessment of kinematic and kinetic patterns following limb salvage procedures for bone sarcoma. Gait Posture 30, 547-551.

Carty, C.P., Bennett, M.B., Dickinson, I.C., Steadman, P., 2010. Electromyographic assessment of gait function following limb salvage procedures for bone sarcoma. J. Electromyogr. Kinesiol. 20, 502-507.

Colangeli, M., Donati, D., Benedetti, M.G., Catani, F., Gozzi, E., Montanari, E., et al, 2007. Total knee replacement versus osteochondral allograft in proximal tibia bone tumours. Int. Orthop. 31, 823-829.

De Visser, E., Mulder, T., Schreuder, H.W., Veth, R.P., Duysens, J., 2000. Gait and electromyographic analysis of patients recovering after limb-saving surgery. Clin. Biomech. (Bristol, Avon) 15, 592-599.

Foucher, K.C., Wimmer, M.A., 2012. Contralateral hip and knee gait biomechanics are unchanged by total hip replacement for unilateral hip osteoarthritis. Gait Posture 35, 61-65.

Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous inference in general parametric models. Biom. J. 50, 346-363.

Otis, J.C., Lane, J.M., Kroll, M.A., 1985. Energy cost during gait in osteosarcoma patients after resection and knee replacement and after above-the-knee amputation. J. Bone Joint Surg. Am. 67, 606-611.

Rompen, J.C., Ham, S.J., Halbertsma, J.P., van Horn, J.R., 2002. Gait and function in patients with a femoral endoprosthesis after tumor resection: 18 patients evaluated 12 years after surgery. Acta Orthop. Scand. 73, 439-446.

Taddei, F., Martelli, S., Valente, G., Leardini, A., Benedetti, M.G., Manfrini, M., et al, 2011. Femoral loads during gait in a patient with massive skeletal reconstruction. Clin. Biomech. (Bristol, Avon) 27, 273-280.

Tsuboyama, T., Windhager, R., Bochdansky, T., Yamamuro, T., Kotz, R., 1994. Gait after knee arthroplasty for femoral tumor. Foot pressure patterns recorded in 20 patients. Acta Orthop. Scand. 65, 51-54.

Whelan, J.S., Jinks, R.C., McTiernan, A., Sydes, M.R., Hook, J.M., Trani, L., et al, 2011. Survival from high-grade localised extremity osteosarcoma: combined results and prognostic factors from three European Osteosarcoma Intergroup randomised controlled trials. Ann. Oncol. 23, 1607-1616.

Woltring, H.J., 1986. A Fortran package for generalized, cross-validatory spline smoothing and differentiation. Adv. Eng. Softw. 8, 104-113.

Table 1. Kinematic, kinetic, and energetic gait parameters of interest

Name	Description
Ground reaction forces	
GF1	Max. aft force
GF2	Max. fore force
GF3	Max. vertical force during early stance
GF4	Max. vertical force during late stance
Joint angles	
H1	Hip flexion at initial contact
H2	Max. hip flexion during early stance
H3	Max. hip extension
H4	Max. hip flexion during swing
H5	H2 – H1
K1	Knee flexion at initial contact
K2	Max. knee flexion during early stance
K3	Knee flexion at toe-off
K4	Max. knee flexion during late stance
A1	Ankle dorsiflexion at initial contact

A2	Max. plantarflexion during early stance
A3	Max. dorsiflexion during stance
A4	Ankle plantarflexion at toe-off
Internal joint moments	
HM1	Max. hip extension moment during stance
HM2	Max. hip flexion moment during stance
KM	Max. knee extension moment during early stance
AM1	Max. dorsiflexion moment during stance
AM2	Max. plantarflexion moment
Joint powers	
HP1	Max. hip joint power during early stance
HP2	Min. hip joint power during late stance
KP1	Min. knee joint power during early stance
KP2	Max. knee joint power during early stance
AP1	Min. ankle joint power
AP2	Mean negative ankle power during stance
AP3	Max. ankle joint power

Abbreviations: Max., maximum; Min., minimum.

Table 2. Patient characteristics at time of measurement

No.	Sex/age, y	Follow-up, mo*	Diagnosis	Site	Endoprosthesis (hinge type)	Revision	Resected muscles and bone length, cm
1	M/59	47	CS	Tibia	HMRS (rotating)	Yes	None, 13
2	M/19	51	OS	Femur	JMM-K5 (hingeless)	No	VL (lateral part), 12
3	M/34	81	GCT	Femur	KLS (fixed)	Yes	None, 12
4	M/24	29	OS	Tibia	HMRS (rotating)	Yes	Soleus (lateral part), 7
5	F/24	34	OS	Femur	KLS (rotating)	No	VI, VM, 13
6	M/24	12	OS	Femur	KLS (rotating)	Yes	VI, VL, 19
7	M/27	61	OS	Femur	JMM K-5 (hingeless)	No	VI (lateral part), VL, 16
8	M/30	111	OS	Tibia	HMRS (rotating)	No	None, 12

*Interval from last surgery (primary or revision).

Abbreviations: CS, chondrosarcoma; GCT, giant cell tumor; HMRS, Howmedica Modular Resection System; JMM-K5, Japan Medical Materials K-MAX KNEE System K-5; KLS, Kyocera Limb Salvage System; OS, osteosarcoma; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis.

Table 3. Sagittal kinematics, kinetics, and energetics

	Ipsilateral, mean (SD)	Contralateral, mean (SD)	Healthy, mean (SD)	*P* value (vs. healthy)*	
				Ipsilateral	Contralateral
Ground reaction forces, %BW					
GF1	16.3 (7.1)	18.5 (2.8)	20.4 (4.5)	.21	.67
GF2	17.8 (4.1)	24.3 (3.8)	20.7 (1.2)	.18	.08
GF3	99.9 (5.7)	110.1 (5.9)	116.7 (7.4)	< .001	.09
GF4	101.6 (3.9)	116.7 (4.4)	109.1 (2.6)	.001	.001
Joint angles, °					
H1	33.2 (5.8)	35.6 (6.2)	33.0 (7.4)	.99	.63
H2	33.2 (5.8)	37.4 (7.4)	33.6 (7.4)	.99	.46
H3	9.5 (6.6)	10.4 (7.5)	11.2 (7.7)	.85	.97
H4	38.4 (7.7)	37.6 (7.5)	34.3 (7.5)	.47	.60
H5	0.0 (0.0)	1.8 (1.6)	0.7 (0.9)	.33	.09
K1	4.4 (5.4)	8.6 (3.6)	10.0 (2.6)	.02	.72
K2	9.2 (8.3)	24.7 (3.2)	25.3 (4.5)	<.001	.98
K3	27.2 (7.0)	36.0 (4.6)	37.8 (2.7)	.001	.70
K4	62.9 (11.4)	64.9 (4.9)	65.7 (2.9)	.67	.96

A1	–2.1 (6.8)	1.6 (3.3)	3.0 (5.1)	.11	.80
A2	11.3 (5.6)	3.5 (2.5)	0.1 (5.2)	<.001	.27
A3	13.9 (4.3)	15.7 (5.2)	20.1 (4.0)	.02	.11
A4	12.2 (8.3)	13.8 (11.2)	7.6 (6.6)	.30	.49
Joint moments, Nm/(kg·m)					
HM1	0.28 (0.11)	0.37 (0.21)	0.24 (0.07)	.75	.15
HM2	0.55 (0.15)	0.57 (0.13)	0.57 (0.12)	.93	.99
KM	0.14 (0.08)	0.40 (0.15)	0.45 (0.12)	<.001	.63
AM1	0.10 (0.07)	0.06 (0.05)	0.05 (0.03)	.17	.82
AM2	0.69 (0.06)	0.89 (0.09)	0.83 (0.06)	.001	.17
Joint powers, W/(kg·m)					
HP1	0.41 (0.20)	0.52 (0.53)	0.24 (0.17)	.53	.21
HP2	–0.68 (0.26)	–0.57 (0.16)	–0.51 (0.17)	.19	.79
KP1	–0.07 (0.08)	–0.52 (0.27)	–0.49 (0.28)	.003	.95
KP2	0.11 (0.08)	0.51 (0.12)	0.52 (0.13)	<.001	.98
AP1	–0.58 (0.10)	–0.51 (0.15)	–0.47 (0.08)	.15	.78
AP2	–0.28 (0.05)	–0.19 (0.06)	–0.19 (0.02)	.001	.97
AP3	2.3 (0.7)	3.0 (0.8)	2.6 (0.4)	.51	.27

[*]Dunnett's test

Figure Legends

Fig. 1 Knee endoprostheses used for the patients. A: Kyocera Limb Salvage System. B: Japan Medical Materials K-MAX KNEE System K-5. C: Howmedica Modular Resection System.

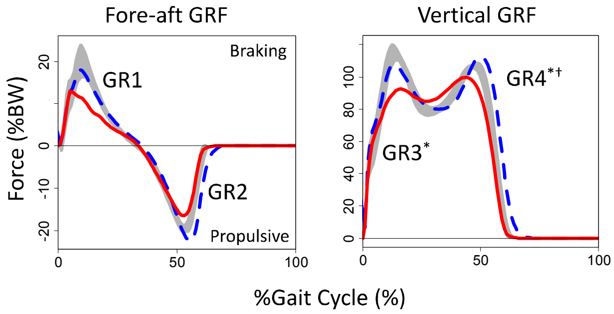
Fig. 2. Ground reaction forces during walking. The solid line and dashed line represent the ipsilateral and contralateral sides, respectively, of the patients. Both lines are the mean values for each group. The gray band represents mean ± 1 SD of the healthy subjects. All data were time-normalized for a gait cycle. $^{*}P < .05$ for comparison between the ipsilateral side of the patients and healthy subjects. $^{\dagger}P < .05$ for comparison between the contralateral side of the patients and healthy subjects.

Fig. 3. Gait kinematics, kinetics, and energetics of each group. The solid line and dashed line represent the ipsilateral and contralateral sides, respectively, of the patients. Both lines are the mean values for each group. The gray band represents mean ± 1 SD of the healthy subjects. All data were time-normalized for a gait cycle. $^{*}P < .05$ for comparison between the ipsilateral side of the patients and healthy subjects. $^{\dagger}P < .05$ for comparison between the contralateral side of the patients and healthy subjects.

Fig. 1

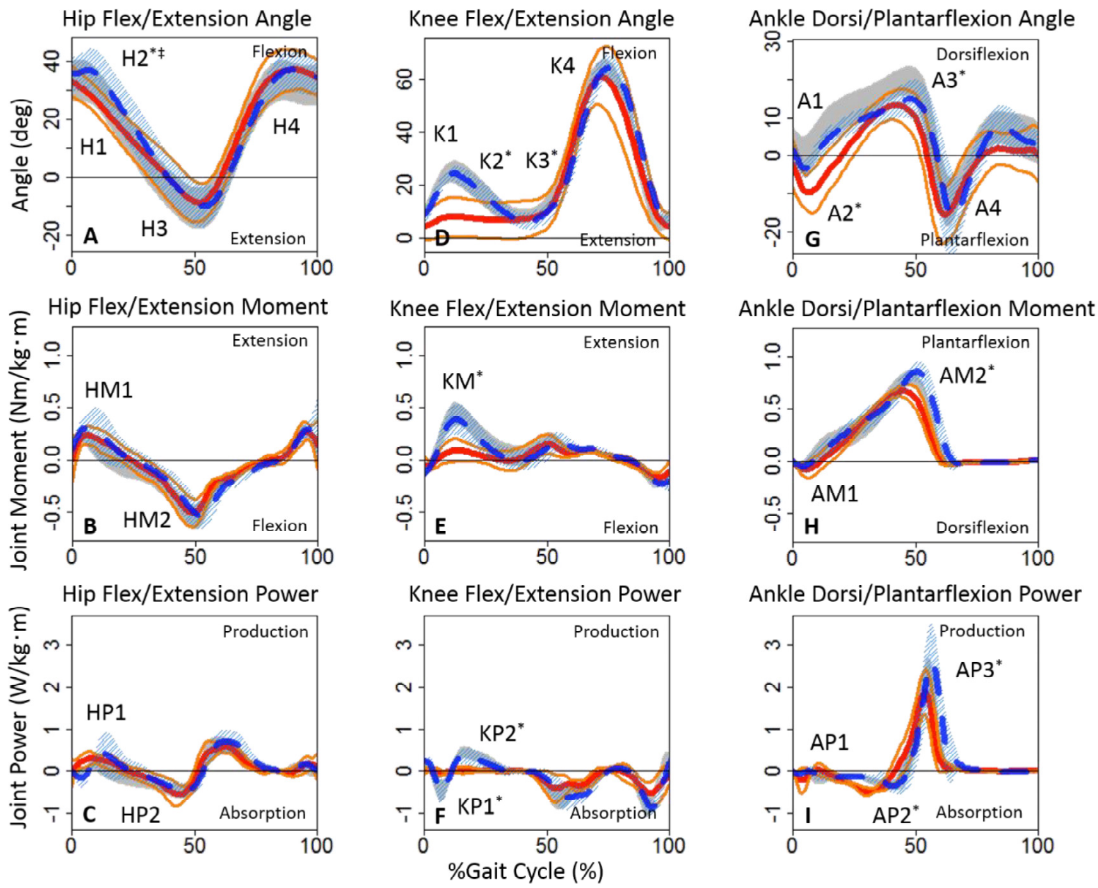
A B C

Fig. 2



Fore-aft GRF
Vertical GRF
Braking
Propulsive
GR1
GR2
GR3*
GR4*†
Force (%BW)
%Gait Cycle (%)
20
0
-10
-20
0
50
100
100
80
60
40
20
0
0
50
100

Fig. 3



Hip Flex/Extension Angle
Knee Flex/Extension Angle
Ankle Dorsi/Plantarflexion Angle
Angle (deg)
H2*‡
H1
H3
H4
Flexion
Extension
A
K1
K2*
K3*
K4
D
A1
A2*
A3*
A4
Dorsiflexion
Plantarflexion
G
Hip Flex/Extension Moment
Knee Flex/Extension Moment
Ankle Dorsi/Plantarflexion Moment
Joint Moment (Nm/kg·m)
HM1
HM2
B
KM*
E
AM1
AM2*
H
Hip Flex/Extension Power
Knee Flex/Extension Power
Ankle Dorsi/Plantarflexion Power
Joint Power (W/kg·m)
Production
Absorption
HP1
HP2
C
KP1*
KP2*
F
AP1
AP2*
AP3*
I
%Gait Cycle (%)